

# A sterile neutrino at MiniBooNE and IceCube<sup>1</sup>

Manuel Masip

*CAFPE and Departamento de Física Teórica y del Cosmos  
Universidad de Granada, 18071 Granada, Spain*

`masip@ugr.es`

## Abstract

We discuss the possibility that a sterile neutrino of mass around 50 MeV slightly mixed with the muon flavor may be the origin of the MiniBooNE anomaly. We show that its production in the atmosphere in a fraction of kaon decays would imply an excess of contained showers at IceCube from down-going and near-horizontal directions.

---

<sup>1</sup>Talk presented at *II Russian-Spanish Congress: Particle and Nuclear Physics at all Scales*, Saint-Petersburg, October 1-4, 2013.

# 1 Introduction

During the past 20 years a number of experiments with solar, atmospheric, reactor and baseline neutrinos have shown that neutrinos have masses and mixings [1]. These experiments provide a framework with

$$\left\{ \begin{array}{l} \Delta m_{12}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2 \\ \Delta m_{23}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2 \\ \approx \Delta m_{13}^2 \end{array} \right\} \left\{ \begin{array}{l} \sin^2 \theta_{12} \approx 0.30 \\ \sin^2 \theta_{23} \approx 0.50 \\ \sin^2 \theta_{13} \approx 0.025 \end{array} \right. \quad (1)$$

that fits remarkably well most of the data. From a model-building point of view the importance of this discovery cannot be overstated. We should, however, keep in mind that

- There are some very basic questions with no answer yet. We do not know, in particular, if these masses are purely electroweak (EW) (just like the electron mass) or if neutrinos are Majorana fermions and their mass is revealing a new scale in particle physics (like radiactivity reveals the EW scale):

$$y_\nu \text{ } HL\nu^c \text{ or } \frac{1}{\Lambda_\nu} \text{ } HHLL ? \quad (2)$$

- There has been a *persistent* anomaly in several experiments with neutrino beams from particle accelerators. Namely, LSND [2] and MiniBooNE [3, 4] have observed an excess of  $\approx 3$  events with an electron in the final state per each 1000  $\nu_\mu$  charged-current (CC) interactions. The interpretation of these events in terms of  $\nu_\mu \rightarrow \nu_e$  oscillations would force the addition of two sterile neutrinos of mass around 1 eV. Here we will go in a completely different direction: we will introduce a sterile mode, but much heavier and unstable. Let us very briefly review these experimental anomalies and the heavy neutrino proposal.

## 2 Gninenko's 50 MeV neutrino at LSND

In the mid 90's LSND [2] observed an excess of electron-like events that were interpreted as  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations followed by a CC interaction giving an electron and a free neutron,  $\bar{\nu}_e p \rightarrow e^+ n$ . In particular, they could see the Cherenkov light of the electron plus a 2.2 MeV photon coming from the capture of the neutron to form a deuteron. Given the LSND fluxes [2], the initial antineutrinos (in Fig. 1–left) were coming from the decay-at-rest of positive muons, whereas the appearance of oscillations would require the existence of a  $\approx 1$

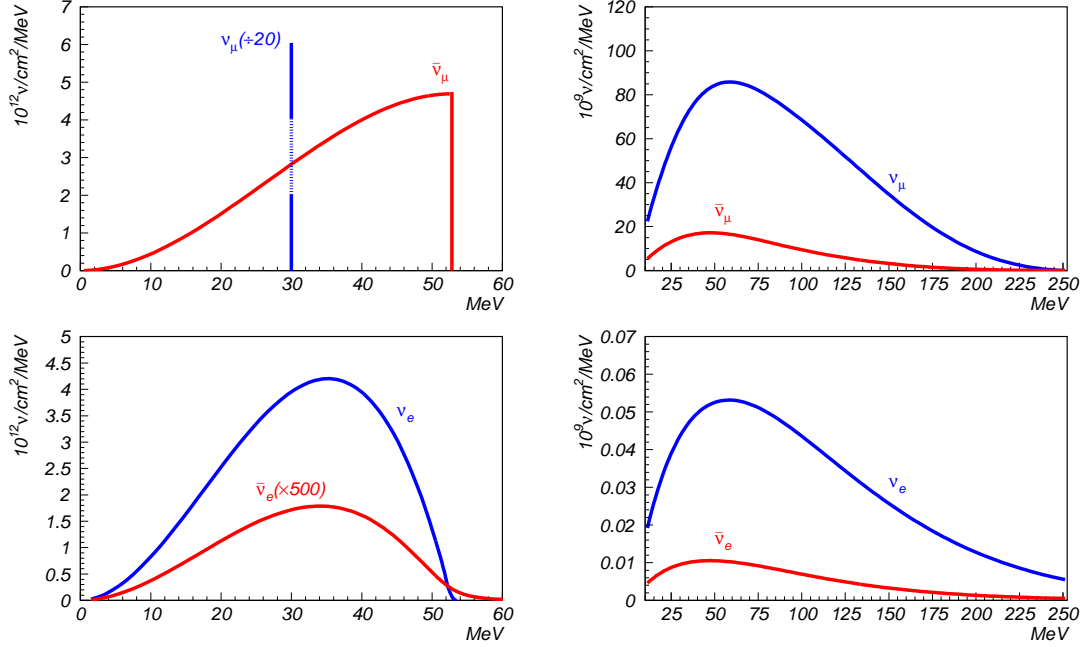


Figure 1: Neutrino fluxes at LSND [2].

eV sterile neutrino slightly mixed with the muon flavor. Instead, Gninenko proposed three years ago a very different interpretation, where the responsible for the signal would be the muon neutrinos from the decay-in-flight of pions (in Fig. 1–right), with energies of up to 200 MeV.

Gninenko [5] showed that these events could be caused by an interaction mediated by a Z boson (see Fig. 2) that changes the initial  $\nu_\mu$  into a sterile neutrino  $\nu_h$  of mass around 50 MeV plus a free neutron. The neutrino should then decay through an electromagnetic (EM) interaction into a light neutrino plus a photon; the photon would finally convert into an electron pair inside LSND giving the same Cherenkov ring as a single electron. In other words, the excess of electron-like events at LSND would actually be due to photon events. For this to work the mixing of  $\nu_h$  with the muon flavor must be relatively large,  $|U_{\mu h}|^2 \approx 10^{-3} - 10^{-2}$ , and the EM dipole transition  $\mu_{tr}$  between  $\nu_h$  and a light neutrino must be such that the lifetime  $\tau_h$  is shorter than  $10^{-8}$  s.

The advantage of Gninenko’s interpretation versus the oscillation hypothesis is that it provides an explanation also for KARMEN [6], that in 2002 tried to reproduce LSND using a similar technique and saw nothing. The initial proton beam and the distances in both experiments were identical, but the larger angle of the neutrino beam selected at KARMEN

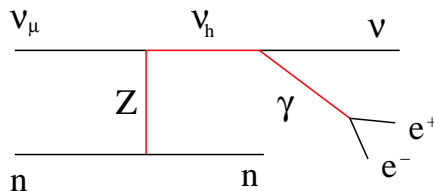


Figure 2: Basic process at LSND in Gninenko's scenario

( $90^\circ$ , versus just  $12^\circ$  at LSND) implied a very different neutrino spectrum: KARMEN eliminated the neutrinos from in-flight decays, keeping only the less energetic antineutrinos from  $\mu^+$  decays at rest. Whereas oscillations should occur in both experiments, the production of a 40–80 MeV neutrino would be above threshold at KARMEN.

This mass and mixing of the sterile neutrino may sound *unlikely*; is there really room for such a particle? Gninenko [5] argues that yes, that  $\nu_h$  could appear instead of a regular  $\nu_\mu$  in up to 1% of all muon and kaon decays. The bounds from current data depend on whether its lifetime is longer or shorter than  $10^{-9}$  s, which corresponds to a decay length of 30 cm. If the heavy neutrino is longer lived then it tends to be invisible (*i.e.*, it does not decay inside the detector) and the kinematic changes that it introduces in kaon and muon decays are not significant. If  $\nu_h$  decays faster (*e.g.*,  $\tau_h = 10^{-10}$  s) then the  $K$  or  $\mu$  decays will appear with an extra photon. It turns out, however, that this is also difficult to see due to background processes with photons,

$$\begin{aligned} \text{BR}(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \gamma) &= (1.4 \pm 0.4)\% \\ \text{BR}(K^- \rightarrow \mu^- \bar{\nu}_\mu \gamma) &= (0.62 \pm 0.08)\% \\ \text{BR}(K^- \rightarrow \mu^- \bar{\nu}_\mu \pi^0) &= (3.35 \pm 0.03)\%. \end{aligned} \quad (3)$$

Although the limits on a 50 MeV neutrino  $\nu_h$  with no decay modes into charged particles are weaker than one may think, a recent analysis of the photon distribution in kaon decays by ISTRA+ [7] disfavors lifetimes  $\tau_h < 10^{-9}$  s. These shorter lifetimes, however, are necessary in the original Gninenko model in order to also explain the low-energy MiniBooNE anomaly (see below). Moreover, it was noticed [8] that Gninenko's model is also in conflict with observations of radiative muon capture at TRIUMF: the shorter-lived heavy neutrino is produced and decays too often there, implying three times more events than observed.

### 3 A variation of the model at MiniBooNE

We propose [9] a variation of Gninenko's model with three basic ingredients.

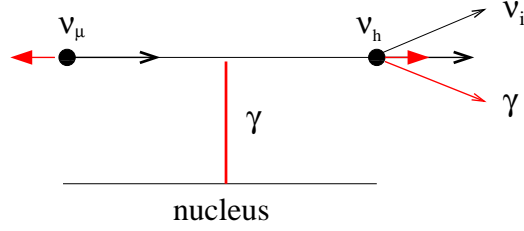


Figure 3: Photon-mediated process at MiniBooNE [9].

- We consider a longer-lived  $\nu_h$  (*e.g.*,  $\tau_h = 5 \times 10^{-9}$  s). The target volume at TRIUMF is smaller than  $c\tau_h$ , and the number of events with  $\nu_h$  decaying inside the detector goes as  $1/\tau_h$  when the lifetime grows. The bounds at ISTRA+ [7] also weaken with an increased  $\tau_h$ .
- We include the EM production of  $\nu_h$  (see Fig. 3). The same EM operator that lets  $\nu_h$  decay into  $\gamma\nu_i$  implies, when the light neutrino  $\nu_i$  is a  $\nu_\mu$ , a production channel at MiniBooNE that was overlooked by Gninenko. The extra  $\nu_h$  produced through photon exchange will dominate and compensate the reduction due to the increased lifetime at MiniBooNE, as some  $\nu_h$  will decay outside the detector. If we write

$$L_{eff} \supset \frac{1}{2} \mu_{tr}^{ih} \left( \bar{\nu}_h \sigma_{\mu\nu} (1 - \gamma_5) \nu_i + \bar{\nu}_i \sigma_{\mu\nu} (1 + \gamma_5) \nu_h \right) \partial^\mu A^\nu, \quad (4)$$

a lifetime  $\tau_h = 5 \times 10^{-9}$  s implies  $(\sum_i (\mu_{tr}^{ih})^2)^{1/2} = 7 \times 10^{-6} \text{ GeV}^{-1} = 2 \times 10^{-8} \mu_B$ , whereas the anomaly at MiniBooNE will require  $\mu_{tr}^{\mu h} = 2 \times 10^{-9} \mu_B$ . This means that only 1% of  $\nu_h$  decays go into a muon neutrino.

- Finally, we impose [9] that the  $\nu_h$  is a Dirac particle: neutrino plus antineutrino of both chiralities. This is important because it will reduce the energy of the events at MiniBooNE. Basically, the initial  $\nu_\mu$  of negative helicity becomes, after the EM transition, a heavy neutrino with the spin pointing (99.9% of the times) forward. It turns out that the decay is then not isotropic and the photon is preferably emitted backwards, with less energy than if it were emitted forward or isotropically. The Dirac nature and the increased lifetime that we have assumed are essential in order to generate an excess only at low energies (higher-energy neutrinos tend to decay outside the detector).

Just like LSND, MiniBooNE is unable to distinguish an electron from a photon converted into an  $e^+e^-$  pair. Our estimate [9] of the number of photon events from  $\nu_h$  decays is given in Fig. 4 for  $m_h = 50$  MeV,  $|U_{\mu h}|^2 = 0.003$ ,  $\tau_h = 5 \times 10^{-9}$  s and  $\mu_{tr}^{\mu h} = 2 \times 10^{-9} \mu_B$ . On the left, we plot with dashes the distribution of heavy neutrinos produced inside the detector

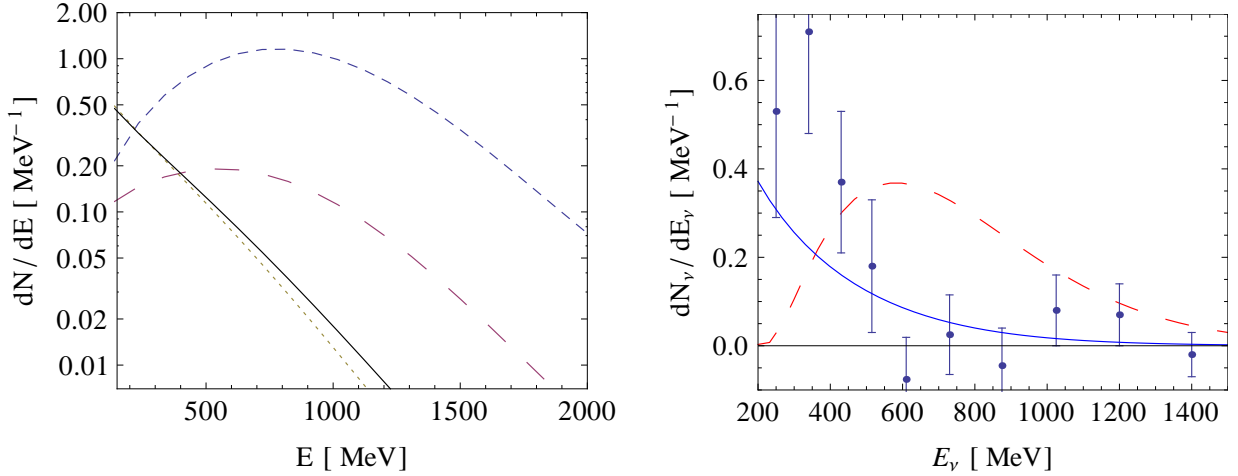


Figure 4: Heavy neutrino events at MiniBooNE in the neutrino mode ( $5.58 \times 10^{20}$  POT) [9].

and with long dashes the distribution of neutrinos that decay inside the detector. Notice that these two lines are closer together at low energies and separate as the energy grows. The dotted line is the energy distribution of the photons (emitted preferably backwards) from the decaying  $\nu_h$ , and the final solid line is the energy assigned to an initial  $\nu_e$  that after a quasielastic collision becomes an electron with the same energy as the photon (*i.e.*, the reconstruction of the photon events as  $\nu_e$  events).

On the right, we plot the excess observed by MiniBooNE with error bars (zero would be consistency with the background) and in dashes what could be expected from  $\nu_\mu \rightarrow \nu_e$  oscillations due to the 1 eV sterile neutrino that explains LSND. The initial publications by MiniBooNE emphasized that their results disprove the LSND oscillation hypothesis, although in the later ones they fail to explain the low-energy excess observed in the data [3, 4]. Our heavy neutrino hypothesis gives a remarkable<sup>2</sup> fit to the data, with similar results for the MiniBooNE excess in the antineutrino mode in Fig. 5.

Three comments are here in order.

- The magnetic dipole transitions that we assume can be generated [11] in left-right symmetric completions of the model at the TeV scale. In particular, we just need that both the left and the right-handed components of  $\nu_h$  define  $SU(2)_R$  doublets together with a charged lepton, and that the breaking of this gauge symmetry gives large mass to this charged lepton while keeping  $\nu_h$  light.

<sup>2</sup>We do not consider significant the different angular distribution of these photon-mediated events discussed in [10]

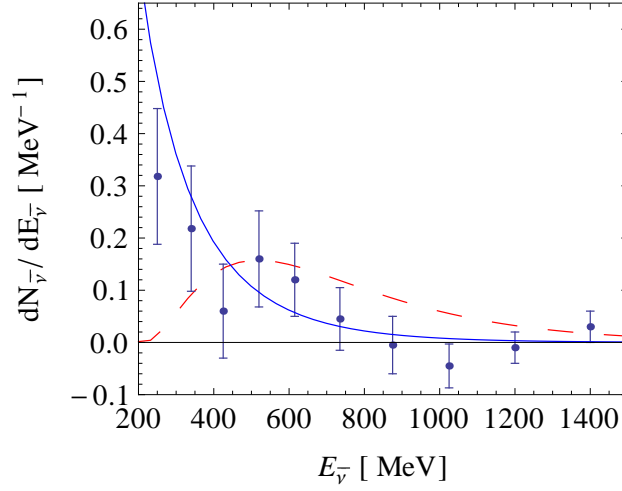


Figure 5: Heavy neutrino events at MiniBooNE in the antineutrino mode ( $11.27 \times 10^{20}$  POT) [9].

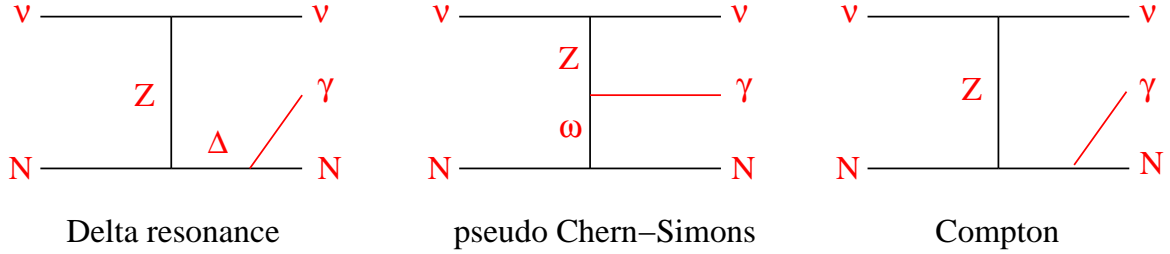


Figure 6: Some background processes producing a photon at MiniBooNE.

- An analysis of T2K (where most of the initial muon neutrinos have oscillated into the tau flavor at Super-Kamiokande) data [12] shows that the decay  $\nu_h \rightarrow \gamma \nu_\tau$  has a  $< 1\%$  branching ratio [9]. Therefore, there must be a second sterile neutrino  $\nu_{h'}$  lighter, longer lived and less mixed with the standard flavors than  $\nu_h$  that accounts for 99% of the decays:  $\nu_h \rightarrow \gamma \nu_{h'}$ .
- MicroBooNE [13] will investigate whether the low-energy excess at MiniBooNE is caused by electron or by photon events. It has been argued [14] that the standard background producing a photon (in Fig. 6) may be underestimated in current simulations. Hopefully, there are observables that may distinguish this background from the  $\nu_h \rightarrow \gamma \nu_{h'}$  hypothesis (in particular, the longitudinal event distribution inside the detector is flat for the background but proportional to  $(1 - e^{-z/\lambda_d}) \approx \frac{z}{\lambda_d}$  in  $\nu_h$  events), so the MiniBooNE puzzle should be settled during the next year.

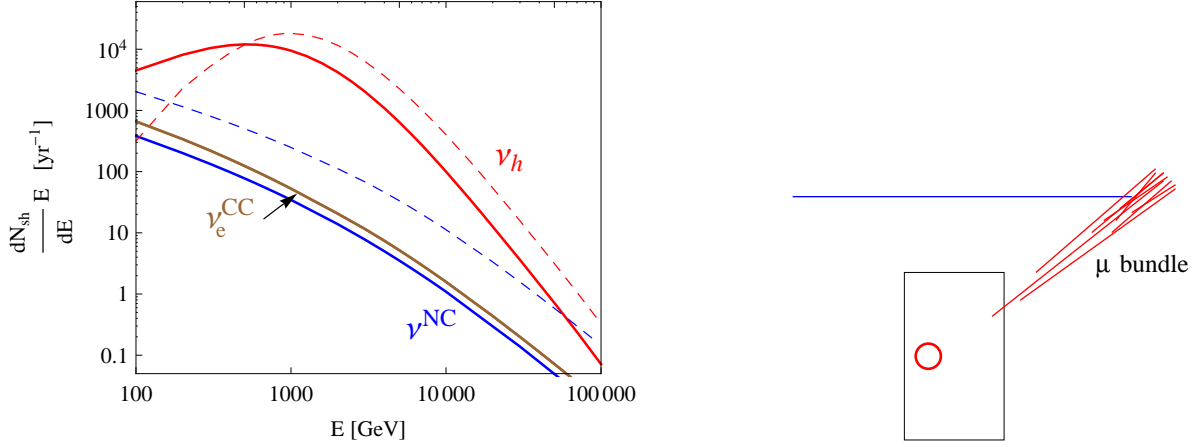


Figure 7: Cascade events at a neutrino telescope from  $\nu_e$  CC interactions,  $\nu_{e,\mu}$  NC interactions, and  $\nu_h \rightarrow \gamma\nu_i$  decays [17]. Neutrinos from charmed-hadron decays, dominant at  $E \geq 10^5$  GeV, have not been included. In dashes, the energy of the parent neutrino (left). Typical  $\nu_h$  event at IceCube (right).

## 4 Implications at IceCube

The LSND and the MiniBooNE anomalies consist of an excess of events with an electron in the final state. The question now would be, could one expect (at larger energies and distances) a similar excess in neutrino telescopes? Would it be detectable?

A telescope like IceCube observes two types of events: muon tracks and point-like energy depositions (hadronic and EM showers develop in  $\approx 10$  m of ice) [15]. The direction of the first ones can be determined very precisely, while in cascade events the error is around  $\pm 15^\circ$ . Upgoing muons crossing the telescope come necessarily from  $\nu_\mu$  interactions (most of these tracks do not start inside the detector), whereas contained cascades from any direction correspond to  $\nu_{e,\tau}$  CC interactions or  $\nu_{e,\mu,\tau}$  neutral current (NC) interactions.

At energies above 100 GeV the flux of atmospheric muons and neutrinos is dominated by kaon decays [16]. Since our  $\nu_h$  appears in up to  $\approx 1\%$  of these decays instead of a muon neutrino, it will be abundant in the atmosphere. Its decay length ( $\gamma c \tau_h$ ) at TeV energies becomes larger than 10 km, so an atmospheric  $\nu_h$  could reach the center of IceCube and decay there. The resulting photon would produce a shower-like event similar to a CC  $\nu_e$  event or to an inelastic NC collision.

We have investigated these processes [17] and have obtained that  $\nu_h$  decays may change substantially the number of contained cascade-like events between 100 GeV (at lower energies



the heavy neutrino can not reach the telescope) and 1 PeV (at very high energies the decay length grows and the probability to decay inside the telescope becomes negligible). In Fig. 7 we have used the Z-moment method to estimate their frequency. Generically, the excess of TeV contained showers introduced by the heavy neutrino has two basic features:

- The excess would only appear in down-going or near-horizontal events (there are no  $\nu_h$  upgoing events)
- Some of these events (specially the ones from small zenith angles) would be contaminated with muons. Since the heavy neutrino is produced in the atmosphere together with a very energetic muon, there will be an excess of *muon plus contained cascade* events.

We would like to conclude by noticing two recent observations published by IceCube. The first one is the sample of 28 events above 30 TeV described in [18], which are indeed very interesting data. If we discount 4 muon-like tracks that are consistent with atmospheric muons entering the telescope, we are left with 24 events that should correspond to neutrino interactions. Three of these events are muons and 21 are cascades. The 3/21 ratio suggests that these events are not atmospheric in origin: below 100 TeV the lepton fluxes are still dominated by kaon and pion decays, which produce more muons than electrons (atmospheric taus are irrelevant). There are just too many cascades relative to muons to be consistent with standard atmospheric-neutrino interactions. The energy distribution of these events is also much flatter ( $\approx E^{-2}$ ) than the one from atmospheric neutrinos ( $\approx E^{-3.7}$ ). Therefore, it is very likely that this is the first observation of cosmic neutrinos. On the other hand, it is *intriguing* that all the cascade events of energy below 100 TeV are down-going or near-horizontal, since at these energies the Earth is not fully opaque (from zenith angles between  $90^\circ$  and  $150^\circ$ ) to neutrinos, and the events observed do not show preference for the galactic disk neither. In our opinion, the data implies an excess of down-going cascade events relative to up-going cascades if one assumes a cosmic origin or relative to muon events if one assumes a standard atmospheric origin, and it could be interesting to run a simulation of the atmospheric  $\nu_h$  hypothesis.

A second interesting observation by IceCube [19] has been obtained in the search for High Light Density events related to magnetic monopoles and other exotics. Although they did not find any monopole candidate, but their cuts selected two events (in Fig. 8) for an estimated background of 0.14 events. It seems to us that these two events are not regular contained showers nor muon bundles, but that they could be interpreted as a cascade event *inside* a muon bundle. Such topology would be difficult to explain with standard model particles, but it is exactly what the heavy neutrino hypothesis would suggest.

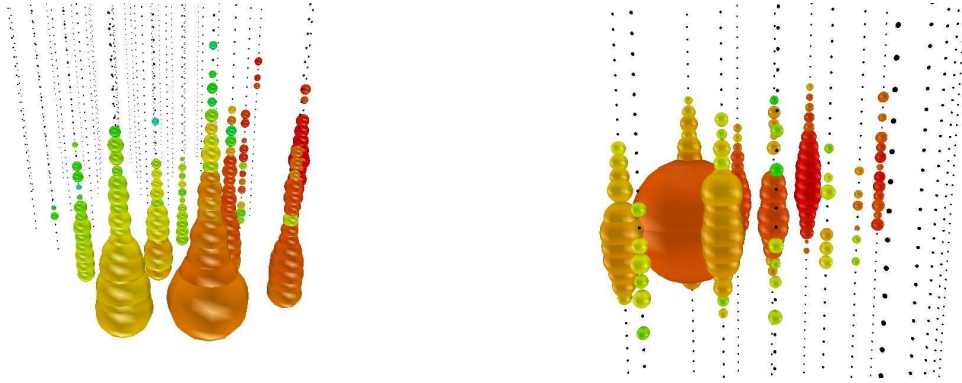


Figure 8: High Light Density events selected in [19].

## 5 Summary and discussion

Neutrino physics has progressed a great deal during the past 20 years, but a few basic questions and some persistent anomalies should still be clarified. We have focused on MiniBooNE and IceCube, that have provided very interesting although still incomplete results. Hopefully, in the near future MicroBooNE and an increased statistics, respectively, will establish the reach of their current results.

We have argued that there is room in neutrino physics for *serious* departures from the three-flavor picture, in particular, we have discussed a 50 MeV sterile mode that could be a solution to the baseline anomalies.

We find the possible incidence of such neutrino in completely different experiments, like neutrino telescopes, very interesting. The heavy neutrino could be produced in the atmosphere and decay inside the telescope, introducing an excess of contained showers from down-going and near horizontal directions, some of them contaminated by atmospheric muons. There seems to be room in current IceCube data for this type of events. Telescopes have the advantage that they are basically background free experiments: each individual event must be explained in terms of neutrino interactions or atmospheric muons. In this sense, the 50 MeV neutrino is a possibility that that may be worth exploring.

## Acknowledgments

This work has been partially supported by MICINN of Spain (FPA2010-16802 and Consolider-Ingenio **Multidark** CSD2009-00064), and by Junta de Andalucía (FQM 101 and FQM 3048).

## References

- [1] J. Beringer *et al.* [Particle Data Group Collaboration], Phys. Rev. D **86** (2012) 010001.
- [2] C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. Lett. **77** (1996) 3082; [arXiv:nucl-ex/9605003]; C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. C **54** (1996) 2685; [arXiv:nucl-ex/9605001]; A. Aguilar *et al.* [LSND Collaboration], Phys. Rev. D **64** (2001) 112007. [arXiv:hep-ex/0104049].
- [3] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. Lett. **98** (2007) 231801; [arXiv:0704.1500 [hep-ex]]. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **102** (2009) 101802. [arXiv:0812.2243 [hep-ex]].
- [4] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **103** (2009) 111801 [arXiv:0904.1958 [hep-ex]]; A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **105** (2010) 181801 [arXiv:1007.1150 [hep-ex]].
- [5] S. N. Gninenko, Phys. Rev. D **83** (2011) 015015. [arXiv:1009.5536 [hep-ph]].
- [6] B. Armbruster *et al.* [KARMEN Collaboration], Phys. Rev. D **65** (2002) 112001. [arXiv:hep-ex/0203021].
- [7] V. A. Duk *et al.* [ISTRA+ Collaboration], Phys. Lett. B **710** (2012) 307 [arXiv:1110.1610 [hep-ex]].
- [8] D. McKeen and M. Pospelov, Phys. Rev. D **82** (2010) 113018. [arXiv:1011.3046 [hep-ph]].
- [9] M. Masip, P. Masjuan and D. Meloni, JHEP **1301** (2013) 106 [arXiv:1210.1519 [hep-ph]].
- [10] A. Radionov, Phys. Rev. D **88** (2013) 015016 [arXiv:1303.4587 [hep-ph]].
- [11] A. Bueno, M. Masip, P. Sanchez-Lucas and N. Setzer, Phys. Rev. D **88** (2013) 073010 [arXiv:1308.0011 [hep-ph]].
- [12] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **107** (2011) 041801 [arXiv:1106.2822 [hep-ex]].
- [13] B. J P Jones, PoS EPS **-HEP2011** (2011) 436 [J. Phys. Conf. Ser. **408** (2013) 012028] [arXiv:1110.1678 [physics.ins-det]].
- [14] R. J. Hill, Phys. Rev. D **84** (2011) 017501 [arXiv:1002.4215 [hep-ph]].

- [15] F. Halzen and S. R. Klein, Rev. Sci. Instrum. **81** (2010) 081101.
- [16] P. Lipari, Astropart. Phys. **1** (1993) 195; J. I. Illana, P. Lipari, M. Masip and D. Meloni, Astropart. Phys. **34** (2011) 663.
- [17] M. Masip and P. Masjuan, Phys. Rev. D **83** (2011) 091301 [arXiv:1103.0689 [hep-ph]].
- [18] M. G. Aartsen *et al.* [IceCube Collaboration], Science **342** (2013) 6161, 947 [arXiv:1311.5238 [astro-ph.HE]].
- [19] J. Posselt, *Search for Relativistic Magnetic Monopoles with the IceCube 40-String Detector*, Ph.D. Dissertation, Wuppertal Univ., October 2013 (<http://elpub.bib.uni-wuppertal.de/servlets/DocumentServlet?id=3814>); R. Abbasi *et al.* [IceCube Collaboration], Phys. Rev. D **87** (2013) 022001 [arXiv:1208.4861 [astro-ph.HE]].